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Technology for Space Optical Interferometry

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Abstract

Optical interferometers are expected to provide the next great leap forward in space based astronomy beyond the Hubble Space Telescope. Various systems are envisioned, ranging from large orbiting structures to lunar based facilities to separated spacecraft flying in formation. Regardless of the specific architecture, these systems will present unprecedented challenges in the measurement and control of optical surfaces, hence driving the technological state-of-the-art in the areas of laser metrology and alignment and stabilization of optomechanical systems. The Jet Propulsion Laboratory has been working for the better part of the last decade to develop and test this technology. Progressing from the derivation and flow-down of requirements through the laboratory demonstration of technology at the component level, the JPL program is now at the point of demonstrating interferometer technology at the system level on a full scale, fall fidelity ground integration testbed. Beyond this lies the Stellar Interferometer Tracking Experiment, a flight demonstration of interferometer technology, paving tbc way for a NASA commitment to the first optical interferometer science mission.

Introduction

Over the past several years a consensus has formed around the idea that space based optical interferometers operating in the ultraviolet, visible, and infrared wavebands represent the next great leap forward in astronomy and astrophysics. Interferometry is the only known method to significantly improve (by orders of magnitude) the angular resolution of current astronomical telescopes and thereby meet several ticy scientific goals of the 21st century: measurement of stellar diameters, resolution of close binaries, extra-solar planet detection, and the precise measurement of galactic and cosmic distance scales. Interferometers lend themselves to space application due to their extremely efficient use of weight and volume to achieve the goals of high resolution, high sensitivity imaging and astrometry. By utilizing the concept of aperture synthesis pioneered in radio astronomy, optical interferometers, whether they take the form of a number of discrete telescopes or a single structure containing Critical portions of one large telescope, allow the space system designer to do more astronomy with less glass. Hence, they represent the only way to take a quantum leap beyond the Hubble Space Telescope at an affordable price (an instrument with ten times HST's resolving power and five times the sensitivity could be launched on any of a number of existing large boosters; an instrument with twice the resolving power and comparable sensitivity could be launched on a Pegasus).

The Astrophysics Division of NASA's Office of Space Science is working to fashion a long range strategy for the space application of optical interferometry. This strategy envisions single structure interferometers in orbit, both for imaging and astrometry, lunar interferometers consisting of discrete telescopes hundreds of meters to kilometers apart, and formations of small spacecraft operating as virtual interferometers where separation distance (and hence optical resolution) is unlimited. Although widely disparate in approach, these system concepts share much in the demands they place on technology development. Recognizing the critical role that the advancement of supporting technologies will play in the success of space optical interferometry, the Astrophysics Division has produced, as part of its AstroTech 21 Program, a "Technology Requirements Plan for Space Interferometry Missions."[1] This plan is synopsized in the next section of this paper.

The majority of the paper is devoted to detailing the efforts underway at the Jet Propulsion Laboratory (JPL) in the development of interferometer technology. These efforts have been funded by NASA's Office of Space Access and Technology, under the auspices of its Micro-Precision Control-Structure Interaction (CSI) Program, and by the Astrophysics Division under its advanced technology development program. JPL's effort is currently guided by the requirements documented in Reference 1. Historically, however, tbc JPL program, begun in 1988, predates Reference 1 and relied for some time on a representative interferometer reference mission as its guiding light. Termed the Focus Mission Interferometer (FMI), this reference mission served as an analytic testbed on which to explore technology requirements and solutions. It has been a remarkably good precursor to Reference 1 and played a central role in the early years of the JPL effort. The principal challenges presented by the FMI are the need to sense the relative positions of optical elements to the order of picometers, to control these relative positions to the order of a nanometer, and to do so over a structure that may span tens of meters. To gauge the severity of these requirements, note that the uncontrolled response of such a system to the expected spectrum of on-board disturbances would result in thousands of nanometers of motion of the optical elements. JPL is developing sensing, and control technologies to address these challenging problems. The paper will discuss, in turn, the analytical application of these technologies to the AIM, the laboratory demonstration of these technologies at the component level, and the integration of these technologies on a full scale, full fidelity interferometer testbed for system level ground demonstration testing. Finally, the paper discusses two proposed flight experiments whose purpose it is to demonstrate that interferometer technology is space mission ready.

Technology Requirements and Priorities

The Technology Requirements Plan for Space Interferometry Missions (Reference 1) is viewed by the Astrophysics Division as a living document which must be periodically updated to reflect NASA's changing mission priorities as well as advances in the technological state-of-the-art. At the time of its first release in early 1993, the Technology Plan reflected the recommendation of the so-called Bahcall Report,[2] written in 1991 by the National Research Council's Astronomy and Astrophysics Survey Committee, chaired by John Bahcall, that a single spacecraft optical interferometer, dedicated to astrometry and dubbed the Astrometric Interferometer Mission (AIM), receive a new mission start from NASA before the year 2000. The two leading contenders for AIM were, and still are, the Orbiting Stellar Interferometer (OSI)[3] and the Precision Optical Interferometer in Space. (POINTS).[4] Hence, the initial version of the Technology Plan was tailored specifically to the particular needs of OSI and POINTS, with longer range interferometer missions, such as orbiting imaging systems, lunar facilities, and multiple spacecraft constellations, receiving essentially no consideration. The situation was somewhat changed at the most recent release of the Technology Plan in August, 1994. Although still considered most likely to be NASA's first interferometer mission, AIM had slipped out of the 1990's for a new mission start, leading the Astrophysics Division to reconsider its long range strategy for space interferometry. This long range strategy is still being formulated. However, the most recent release of the Technology Plan addresses a broader spectrum of potential interferometer missions, while still placing its greatest emphasis on AIM. Not surprisingly, it turns out that the various classes of optical interferometers share considerable commonality in their technology needs. This is reflected in Table 1 which rates the relative priority of the relevant technologies against the interferometer mission

Table 1.

TECHNOLOGY AREA	SPACE INTERFEROMETRY MISSION CLASS			
	ASTROMETRY (AIM)	ORBITAL IMAGING INTERFEROMETER	LUNAR INTERFEROMETER	MULTIPLE SPACECRAFT CONSTELLATION
PICOMETER METROLOGY	HIGH	HIGH	HIGH	HIGH
INTEGRATED MODELING	HIGH	HIGH	HIGH	HIGH
VIBRATION ISOLATION & POINTING	HIGH	HIGH	MEDIUM	HIGH
ACTIVE DELAY LINES	HIGH	MEDIUM	HIGH	HIGH
QUIET STRUCTURES	HIGH	HIGH	MEDIUM	MEDIUM
PRECISION DEPLOYMENT	HIGH	HIGH	MEDIUM	MEDIUM
THERMALLY STABLE OPTICS	MEDIUM	MEDIUM	HIGH	MEDIUM
ADVANCED MATERIALS	MEDIUM	MEDIUM	MEDIUM	MEDIUM
ELECTRIC PROPULSION	LOW	LOW	LOW	HIGH
CONTAMINATION PREVENTION SYSTEMS	LOW	LOW	HIGH	LOW
GROUND INTEGRATION TESTBEDS	HIGH	HIGH	HIGH	HIGH
FLIGHT EXPERIMENTS	HIGH	HIGH	HIGH	HIGH

classes. Hence, the Technology Plan continues to prioritize technology needs using AIM as the yardstick. To quote from the Plan:

"Once implemented, AIM will set the standard for precision in space system alignment, stabilization, and knowledge. High precision metrology (~20 picometer 1-D relative measurement accuracy), within an element and between elements of an interferometer, is a driving technology requirement. Of comparable importance is the requirement to maintain mechanical stability of the optical system to the 10 nanometer level. AIM is the prototype for future mission concepts that employ more than one aperture. Baselines [between apertures] may be up to 30 meters in extent in space and hundreds of meters on the moon. Although this document concentrates on the technology needs of AIM, development of the capabilities called for in this plan will go a long way toward enabling more advanced interferometer systems as well."

Note that the 20 picometer metrology requirement derives from the astrometry science, which requires knowledge of the interferometer baseline vectors to a fraction of a nanometer in order to achieve astrometric precision below 10 microarcseconds. The 10 nanometer mechanical stability requirement is analogous to the $\lambda/20$ wavefront quality requirement typical of all high-quality optical systems. This level of mechanical motion is consistent with maintaining high contrast on the interference fringes formed on an interferometer's science detectors.

The technology plan goes on to set technology priorit its, at the component level, as follows:

1. Metrology and Starlight Detection Systems
2. High Fidelity Integrated Modeling
3. Fine Pointing and Vibration Isolation
4. **Active 1**)elay Lines and Siderostats
5. Quiet Structures and Subsystems, Precision Deployment

No(c that priorit y #1 addresses the 20 picometer relat ive measurement requirement, priorities #3 - #5 address the 10 nanometer mechan ical stability requirement, and priority #2 recognizes the necessity of efficiently and accurately modeling the complex, multidisciplinary system that an interferometer is. The Technology Plan goes on to state:

"[n addition to the above component technology, OSI and POINTS both require, as a highest priority, system in tegration testbeds for va lida tion o f component hardware, verification o f in tegrated modeling soft ware, and end-k-end performance demonstra tion. Flight experimentation will also be required where critical fun ctionality cannot be demonstrated without the presence of the space environment.' "

The Focus Mission Interferometer (FMI)

As discussed in the Introduction, JPL's interferometer technology development program predates the Technology Plan and was guided during its early years by the Focus Mission Interferoi neter (FMI) reference mission. Figure 1 shows a sketch of the FMI in its deployed configuration. An interferometer is fundamentally a sparse aperture optical system where spatially distributed "small" collecting apertures arc combined to synthesize the performance of a single larger aperture. In the case of the FMI, the six 0.5 meter collecting apertures are arranged in a linear array across the structure to form three distinct interferometers. An optical interferometer can be used for high resolution imaging as well as extremely precise astrometry (astrometry is the mapping of stellar positions in the sk y). When used for imaging, the FMI's effective baseline of 24 meters would give it roughly 10 times the resolving power of the Hubble Space Telescope. This translates intoa resolution of 5 milliarcseconds. By way of comparison, Figures 2 and 3 show OSI, a 7-meter baseline system containing three interferometers in a linear array, and POINTS, **whose** box-like instrument compartment contains two 2-meter interferometers oriented perpendicular to one another. Since the FMI was assumed to operate well into the ultraviolet (down too. 12 microns), its requirements for the sensing **and** control of optical elements arc roughly four times tighter

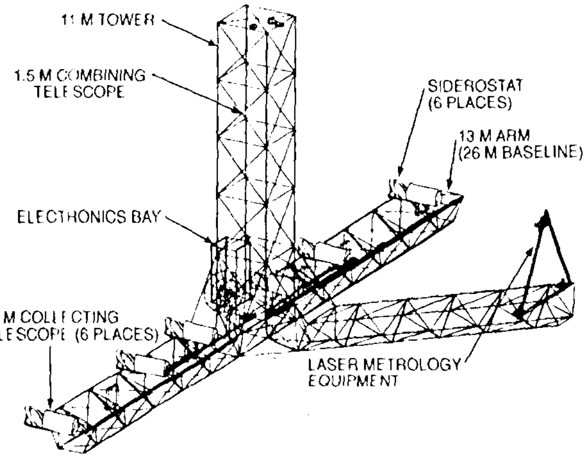

Fig. 1. Focus Mission Interferometer Configuration.

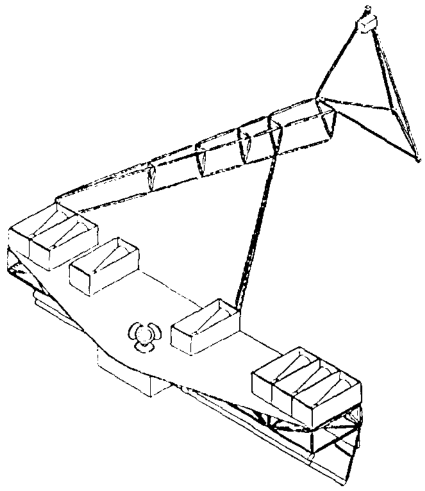

Fig. 2. The Orbiting Stellar Interferometer (OSI).

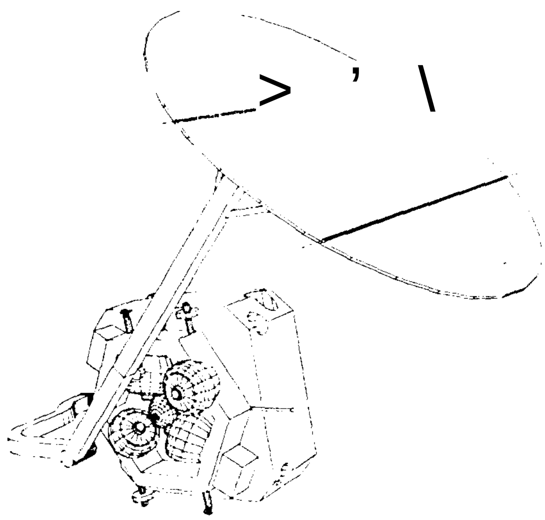

Fig. 3. Precision Optical interferometer in Space (POINTS).

than those of the AIM candidate systems, which are conceived as visible instruments. Nevertheless, the FMI requirements (S picometers RMS relative metrology sensing, *2.5* nanometers RMS mechanical stability) are equivalent to those of AI M to the extent that they arc used to set technology priorities and drive technology development.

The optical performance of the FM I relative to its 2.5 nanometer differential pathlength stabilization requirement has been analyzed in some detail with the conclusion that **vibration attenuation factors of between 1,000 and 10,000** arc necessary to meet the requirement with margin. This is one of the principal challenges that interferometer technology must address. Vibration attenuation alone is not sufficient, however. The need to operate well under a micron in absolute stability represents a significant challenge in its own right. in addition to exposing the severity of the performance requirements, analysis of the FMI pointed up major deficiencies in the existing capability to design and model (in an end-to-end fashion) complex optics/structure/control systems subjected to mechanical and thermal disturbances. This challenge must be met in order to make it practical to conduct quantitative design trades early in the design process and to enable simulat ion of system performance prior to fabricat ion and test. On the sensing front, the challenge of performing laser metrology measurements to a fraction of an Angstrom is quite severe. The final challenge is to demonstrate, to those entrusted with making NASA mission decisions, that interferometer hardware, software, and methodologies arc mature and ready for application to flight systems. The remainder of this paper is organized around illustrating, in turn, how JPL is addressing each of the major challenges posed above.

Meeting the Vibration Attenuation Challenge

The first challenge for an FMI class optical systems is providing three to four orders of magnitude vibration attenuation. Addressing this challenge has been the province of the JPL Micro-Precision Control-Structure interaction (CSI) Program, which has adopted an approach that entails a **malt i-layer architecture**, with cacb layer responsible for providing between onc and two orders of magnitude attenuation. Currently three layers - vibration isolation, active/passive structural quieting, and optical element compensation - arc considered sufficient to meet the performance requirements of systems like the FMI. The idea is to intercept disturbance energy at the source (via vibrat ion isolat ion), along the transmission path (via structural quieting), and at the destination (via high bandwidth optical compensation). Each layer will have a specific realization tailor-cd to the system under considerat ion. For the FMI, the structural **quieting** layer is comprised of 25 **active members whose** locations and electro-mechanical impedances have been optimized to dissipate kinetic energy from tile truss structure. The vibration isolation layer is similar to that implemented on the Hubble Space Telescope (HST) reaction wheels (i/W's). Improved performance, over that of Hubble, is achieved by augmenting the HST's passive system with active control using voice coil actuators. The optical compensation layer consists of both tip/tilt control on siderostats and fast steering mirrors as well as transition control stages to con ect and stabilize optical pathlength through the system. An overall closed loop bandwidth of 2S() Hz has been simulated for the pathlength control loop, with a PZT providing the vernier high bandwidth actuation. For the vibration analysis, the disturbance source used was the imbalance force from 4 HST RW's spinning from () to 3000 RPM (**i.e.,** 50 Hz).

Figure 4 shows pathlength error for the FMI's outermost interferometer as a function of RW speed. Notice that, without control, the response exceeds the 2.5 nm requirement at virtually every RW speed, and in several speed ranges exceeds 1,000 nm. In **an** RMS sense, the Uncontrolled pathlength response is greater than 700 nm across all wheel speeds. As layers of control arc added - structural quieting, vibration isolation, and pathlength control, in turn - RMS vibration attenuation factors of 5, 20, and 7 arc achieved, respectively. The resultant 3-layer RMS attenuation factor of 700 means an RMS pathlength stability of just over 1 nm. In a 3-sigma sense, a wor st case pathlength error of 10,000 nm is reduced by a factor of 1,000 to 10 run.

Clearly, in the world of computer simulation, the CSI multi-layer architecture appears to be capable of meeting the three to four orders of magnitude vibration attenuation

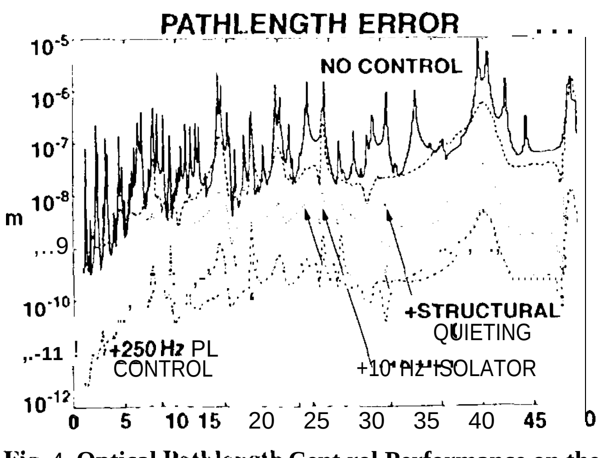

Fig. 4. **Optical Pathlength Cent rol Performance on the Focus Mission interferometer (Meters vs. Reaction Wheel Speed in Hz).**

requirement. The next question is whether this conclusion holds up on actual physical systems under laboratory conditions.

Experimental Demonstration of The Multi-Layer Architecture

To experimentally demonstrate that the multi-layer architecture can meet this challenge, and prove that the successive layers are not unstably interactive, JPL has built a dedicated test facility called the CSI Phase B Multi-Layer Testbed.[5] The Phase B Testbed has been built to resemble a portion of an interferometer telescope, including a laser star simulator, a metering truss structure, an optical pathlength delay line, and the associated instrumentation and real time control computers. It has proven to be an excellent setting in which to investigate the blending of the three layers of the multi-layer architecture: structural quieting, vibration isolation, and optical compensation. Figure 5 depicts the testbed and points out each layer of control. The disturbance is mounted on a single axis vibration isolation stage. The disturbance transmissibility (i.e., transfer function) from this source to optical pathlength stability (as measured by a fringe detector monitoring the laser "star simulator" signal) represents the figure of merit for experiments conducted on the testbed

The Structural Quieting Layer

Lightly damped resonances in structures amplify the effects of disturbances and result in much greater levels of vibration and jitter. Structural vibration in turn causes misalignment in the optical train. Precision structures generally manifest low levels of damping because energy dissipating mechanisms such as friction are eliminated due to the precise tolerances of the joints and connections.

The CSI structural quieting layer is specifically designed to reduce the level of vibration in the structure. This is accomplished through a combination of passive damping and active control using active structural members. Passive dampers have the advantages of simplicity of design and of requiring no power for operation. Four Honeywell D-Strut[6] passive dampers are installed in the Phase B Testbed (Figure 6). Active structural members[11] which utilize an embedded piezoelectric or electrostrictive actuator, have the advantage of being tunable for optimal performance even after the structure has been assembled and/or deployed. The active dial-a-strut control circuit cannot only be tuned to emulate passive dampers, but can also be designed to achieve a more exact impedance match to the structure, providing damping performance tailored to frequency.[12] Four JPL designed active members are installed in the testbed (Figure 6). The active and passive members have

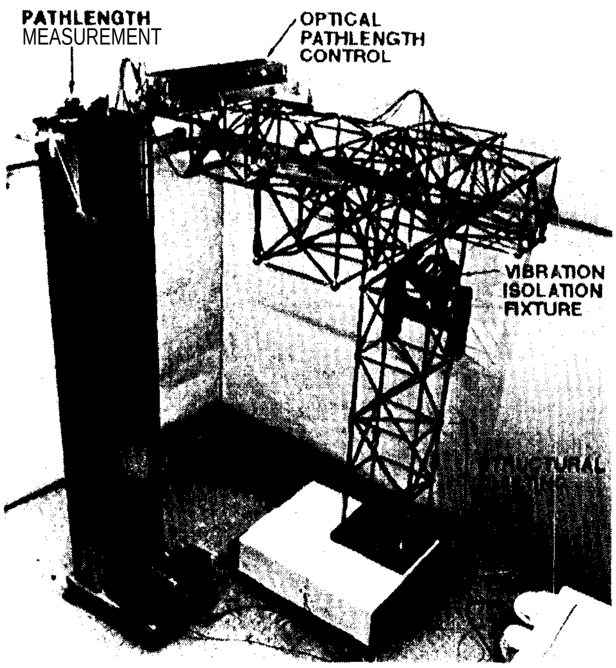

Fig. 5. Phase B Multi-Layer Testbed.

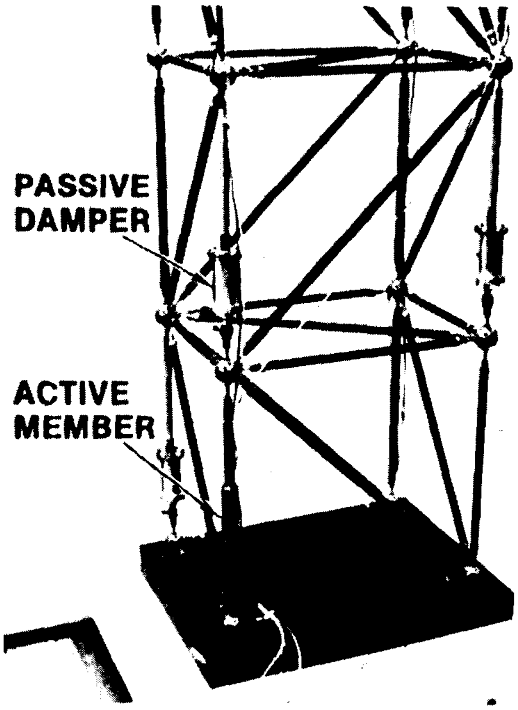

Fig. 6. Structural Quieting Elements in Phase B Truss Structure.

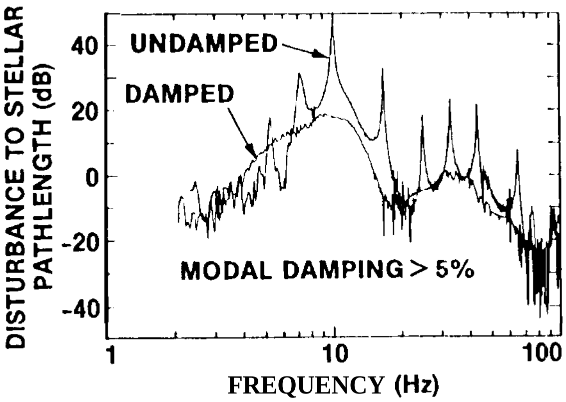

Fig. 7. Disturbance Attenuation Due to the Structural Quieting Layer.

been optimally located in the structure through the use algorithms designed to minimize disturbance transmissibility from the disturbance source to the optical pathlength metric[13,14] The performance of the structural quieting layer, in terms of disturbance attenuation, is seen by comparing the two transfer functions depicted in Figure 7. All modes below 80 Hz exhibit damping exceeding 5% of critical, compared to damping ratios between 0.1 % and 1.0% in the undamped structure. in addition to providing reduced disturbance transmission through the structure, the structural quieting layer has a stabilizing effect on the other layers of control, especially the high performance optical compensation layer. This stabilizing effect leads directly to higher bandwidth optical control, which in turns results in at least a factor of 5 improved disturbance rejection.

Recently the active member has taken a major step forward toward flight qualified status. The solid state actuator technology at tile heart of the active member was flown successfully in the Actuated Fold Mirror (AFM) as part of the Hubble Recovery Miss ion.[15] The AFM is an opt ical component in the new Wide Field/Planetary Camera (WF/PC-2) which was successfully installed in the HST by astronauts in December of 1993. The AFM uses electrostrictive actuator technology, originality developed by Litton/Itek Optical Systems for Department of Defense deformable mirror applications. Because electrostrictive actuator technology is relatively new, the HST recovery mission represents its first space flight application. The research that supported the AFM for Hubble will continue to advance the readiness of precision active members that will be effective in precision alignment and structural quieting applications. The successful flight of the AFM gives tremendous impetus for incorporat ion of CSI active member technology in near term flight missions.

The Disturbance Isolation Layer

Vibration isolation is the first line of defense against the performance threatening effects of mechanical disturbances on-board micro-precision systems. For applications where the most significant disturbance sources (e.g., reaction wheels, tape recorders, etc.) can be housed together in a single "dirty box," the vibration isolat ion layer, in the CSI multi-layer architecture, is likely to provide the greatest performance enhancement at the lowest cost. This is because isolation can be implemented by a single six axis device, whereas the other layers (viz.., structural damping and optical compensation) typically entail numerous hardware components distributed over the system. In such situat ions the vibration isolation layer, if sufficiently effective, will significantly relax the requirements on (if not eliminate the need for) one or both of the other layers.

A disturbance isolation fixture was designed, built, and implemented on the JPL Phase B Testbed (Figure 8). The disturbance source was a proof-mass shaker suspended on an accordion type flexure which in turn was rigidly attached

Fig. 8. Phase B Testbed Disturbance Isolation Fixture.

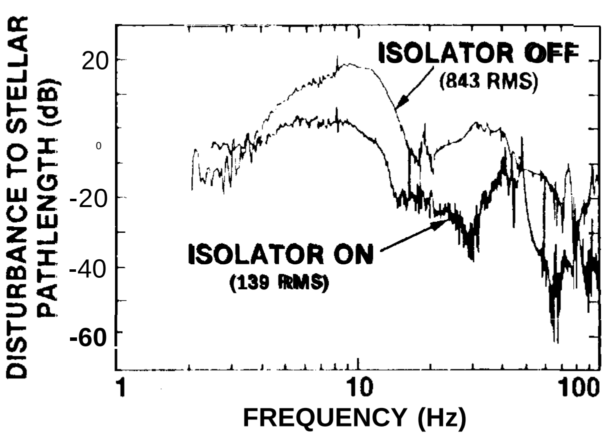

Fig. 9. Disturbance Attenuation Due to the Vibration isolation layer.

to the truss structure. The corner frequency of the soft mount was measured at 3 Hz with natural damping on the order of 12% of critical. An active stage consisting of a voice coil actuator and an LVDT displacement sensor was added in parallel with the soft mount. Active control experiments using positive position feedback (PPF) were successful in reducing the corner frequency of the isolator by a factor of 2 over the passive design. The experimental results (Figure 9) show the improvement in optical performance when the isolator is turned on. A broadband RMS attenuation factor of greater than six was achieved.

Recent improvements in isolator design have enhanced this performance by another factor of five.[16] The compact single-axis device pictured in Figure 10 has demonstrated 30 dB of broadband vibration isolation (Figure 11). Recently JPL built a six-axis unit (Figure 12) consisting of six single-axis devices configured as a "Sewart Platform." In theory such a unit should be capable of fully isolating a micro precision spacecraft from all translational and rotational disturbances. This theory will be put to the test in the immediate future as the device of Figure 12 undergoes performance testing.

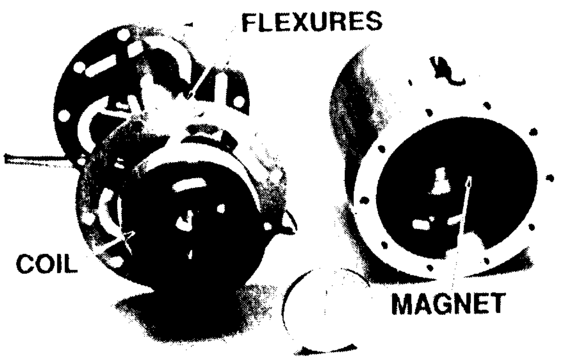

Fig. 10. Soft Active Member (SAM) Isolation Strut.

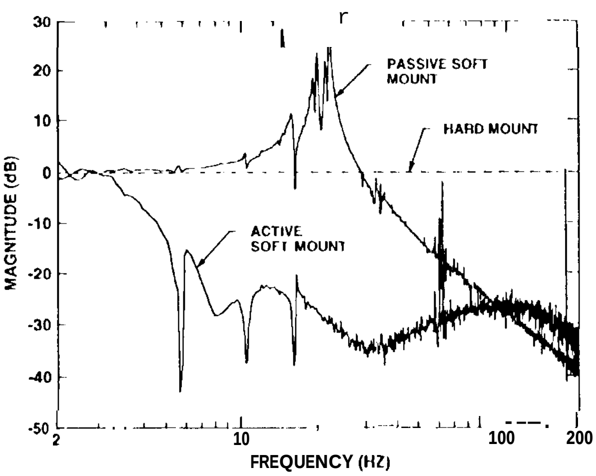

Fig. 11. SAM Isolation Performance.

The Optical Compensation Layer

The optical delay line experiment was designed to capture the interaction between structural flexibility and optical pathlength as it would occur in a space-based optical interferometer such as the FMI.[17,18] Varying levels of control/structure interaction can be emulated by reconfiguring

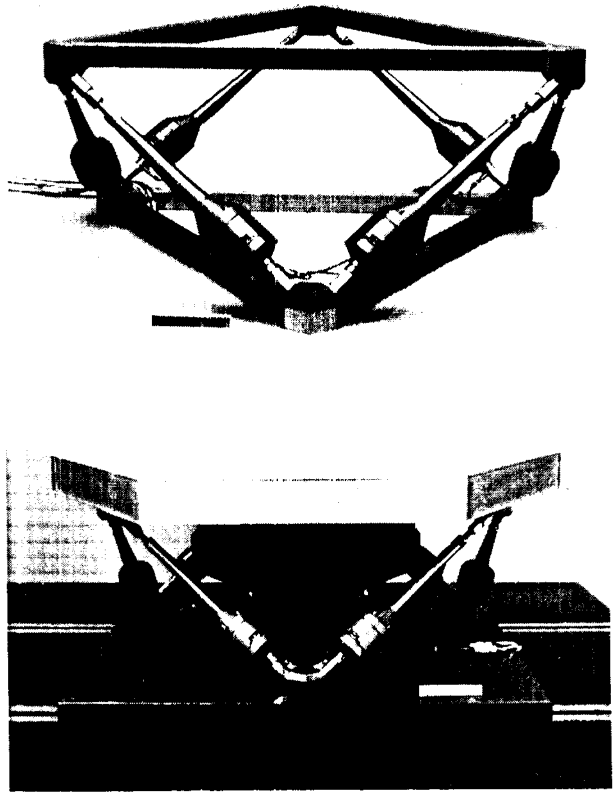

Fig. 12., 11'1, "Hexapod" Isolator — Shown With and Without Mounted Disturbance Source (viz., Reaction Wheel).

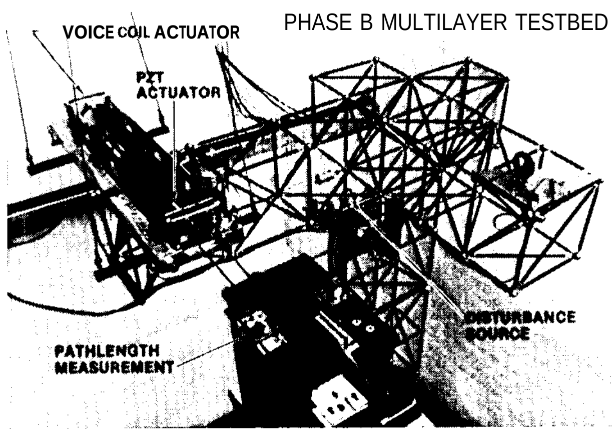

Fig. 13. The Optical Compensation System on the Phase B Testbed.

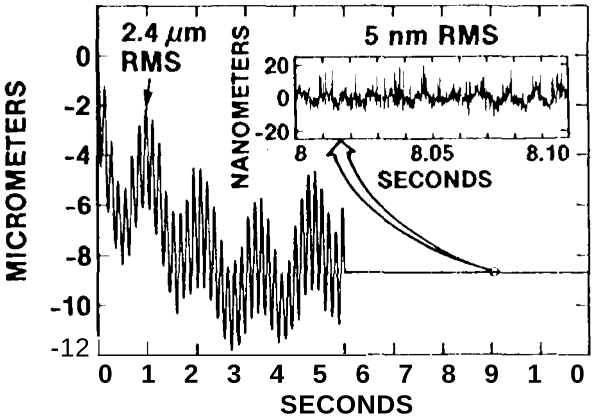

Fig. 14. Optical Pat hlength Response to Shaker induced Sinusoidal Excitation — Cent rol Loop Closed After S Seconds.

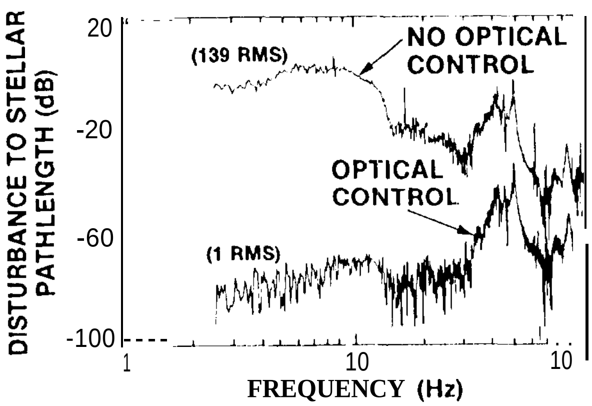

Fig. 15. Disturbance Attenuation Due to the Optical Compensat ion 1 ,ayer.

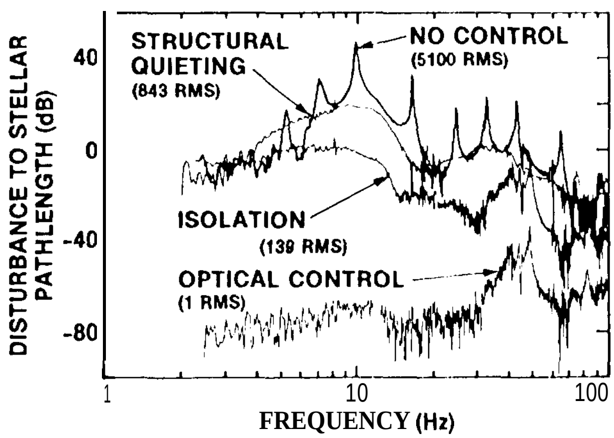

Fig. 16. Disturbance Attentuation on the Phase B Testbed with All Layers Operating.

the testbed optical train. The configuration shown in Figure 13 represents a typical case for an interferometer, where the laser beam bounces off mirrors located on opposite ends of the truss structure. Vibrational mot ions of the mirrors in the path of the laser twain change the length of the optical path and this change is measured interferometrically by a fringe detector. Control of the optical pathlength is provided by a coarse motion voice coil act uator and a fine motion piezoelectric actuator.

With the testbed excited at the natural frequency of a major structural mode, closed loop experimental results indicate (Figure 1 4) that stellar pathlength variations were reduced from 2.4 micrometers RMS to approximately 5 nanometers RMS (the testbed noise floor). in addition, it was demonstrated that if a white noise disturbance excited the structure with energy uniformly distributed over 1--100 Hz, the optical control layer would reject it by a factor of 139 RMS (see Figure 15).

Multi-Layer Performance

The nIL]lti-layer experimental results arc given in terms of the disturbance transmission function from disturbance source to optical pathlength. The frequency response plot of Figure 16 summarizes the results and shows how each layer, implemented successively, lowers the disturbance transmission function. Assuming that a ban(i-limited white noise disturbance excites the structure with energy uniformly distributed over 1-- 100 Hz, the RMS attenuation factor achieved by each layer in that frequency band is: (i) structural quieting: 6; (ii) disturbance isolation: 6; (iii) optical control: 139.

With all layers operating together, the multi-layer architecture enables a **5100:1 vibration reduction.**[19] Clearly, the biggest contributor to vibration attenuation performance is the optical control layer. However, the structural quieting layer was essential in enabling this level of optical compensation. Without the level of damping introduced by structural quieting, the optical control bandwidth would have been reduced by at least a factor of 3 (in order to preserve system stability), resulting in a factor of 5-10 poorer vibration attenuation. This recognit ion leads us to regard the opt ical compensation and structural quieting layers as essent ially equal contributors (factor of 30 each) to overall vibration attentuation performance. Also of note is the achieved level of absolute optical pathlength stability in the ambient labor story environment: S **nanometers RMS. The** principal contributors to this residual level were fringe detector resolution (~2 rim), noise in the control electronics, and laboratory acoustic and seismic excitation. Since the latter two noise sources arc not present in space, and the former two are readily dealt withby near term improvements in electronics design, the promise of sub-nanometer stabilization of space optics appears quite feasible.

Experimental Demonstration of Picometer Laser Metrology

The measurement technology needed to support the work in nanometer regime mechanical control discussed above is essentially at the commercially available state-of-the-art. In some cases custom designed read-out electronics were necessary to process the signals from commercial laser interferometers at higher rate or greater resolution. However, the need for picometer laser metrology to enable optical interferometers like OSI and POINTS to do microarcsecond astrometry drives the technology considerably beyond the state-of-the-art.

Remarkable progress has been made in this area recently[20,21]. Experiments conducted at JPL have at least established the feasibility of picometer relative metrology. These experiments utilize a heterodyne laser gauge, shown in Figure 17. The heterodyne laser gauge used a stabilized 0.633 μm He-Ne laser as the light source. The light is separated into two polarizations and modulated at different frequencies using acousto-optic modulators (AOMs). One polarization travels between the two corner cubes and is interfered with its orthogonal polarization using a 45° polarizer. The phase of the detected beat frequency measures changes in the distance between the two corner cubes. A 2π phase change corresponds to a λ/2 distance change. The experiments reported here were conducted in vacuum with the corner cubes separated by a nominal distance of 75 cm. Two different implementations of the basic heterodyne gauge architecture were examined. A null gauge was studied to determine the ultimate precision of a heterodyne interferometer by using two gauges with spatially coincident beams. The deviation between the two readouts is taken to be the precision of the gauge itself. A relative gauge, where the beams are spatially separated, was also examined to determine the extent of systematic errors which are absent in the null configuration.

The initial null gauge experiments were conducted in the early spring of 1992. The results showed a null gauge precision of 0.6 picometer at integration times (averaging periods) of 2,500 seconds. The main contribution to this tiny error was determined to be due to temperature drifts in the electronics. The performance of the relative gauge is more indicative of the performance that can be expected of an ultimate flight metrology system. In the relative gauge experiments, one of the two heterodyne gauges is used to servo the distance between the corner cubes to a slowly varying separation while the other gauge is used as a read-out device. The relative metrology experiment is designed to classify and eliminate various sources of systematic errors which are absent in the null metrology gauge. The polarization leakage caused by several imperfect optical elements causes a systematic error at the output of the interferometer which is a periodic function of the distance between the corner cubes, with a period of exactly one wavelength. The amplitude of this systematic error can be as large as 10 nanometers. Non-periodic systematic errors appear as smaller drifts due to time varying temperature gradients in the optics as well as linear drifts that can be correlated to the distance between the corner cubes. These latter linear drifts (on the order of 10's of picometers per wavelength of corner cube motion) can thus be calibrated as a function of the corner cube distance and eliminated. The large periodic error due to polarization leakage can be eliminated by using a method known as cyclic averaging.[20] This is implemented by modulating the distance to be measured (i.e., the distance between corner cubes) over an amplitude of several wavelengths with a piezoelectric transducer. The resulting

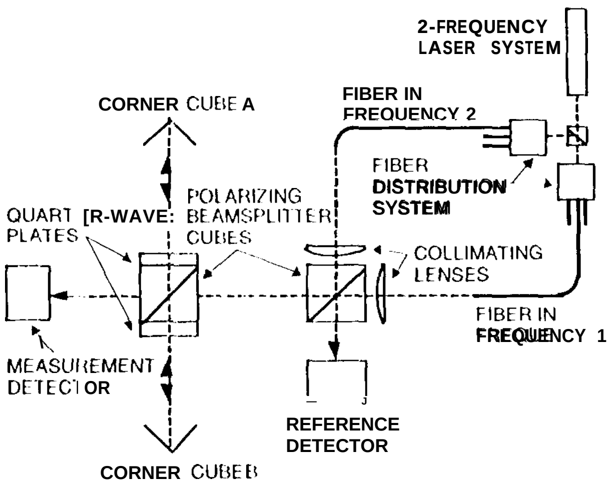

Fig. 17. Heterodyne Laser Gauge.

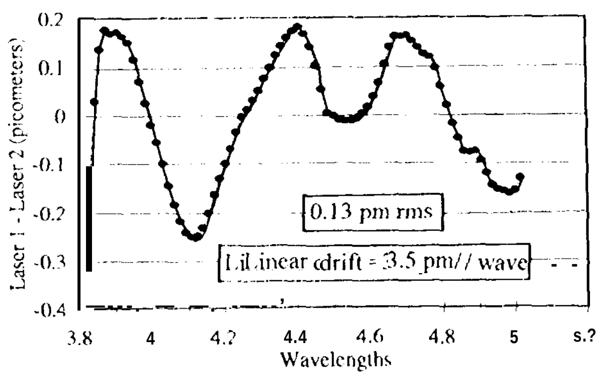

Fig. 18. Residual Relative Metrology Error, Temperature Stabilized Experiments (error in picometers vs. waves of corner cube motion).

residual error, averaged over approximately 10 minutes of data, was 3.5 picometers. Subsequent experiments[21] were run under more lightly stabilized thermal conditions to eliminate relative thermal drifts between the two heterodyne gauges. Figure 18 shows the metrology data taken during the time interval with the smallest change in temperature. The calibratible linear drift is 3.5 picometers per wave of motion, and has been removed from the plot. The residual error is 0.13 picometer RMS. The fact that this result is better than the performance of the null gauge is attributed to the great care taken with thermal control during the second set of relative gauge experiments.

Clearly, considerable work is yet to be done to take picometer metrology from the tightly controlled environment of a laboratory vacuum Chamber to the robust and rugged hardware needed for space flight. Nevertheless, these recent experiments represent a major step forward in that they establish that conducting laser based measurements at the picometer level is feasible.

Integrated Modeling and Design Tools for Interferometer Systems

The challenges facing space interferometry do not lie exclusively in the province of developing hardware for laser metrology and vibration attenuation in the sub-micron regime. Work is also needed to advance the state-of-the-art for software tools for analysis and design. Existing analysis tools provide only limited capability for evaluation of spaceborne optical system designs. They determine optical performance from the geometry and material properties of the optical elements in the system, assuming only minor deviations from the nominal alignment and figure. They cannot evaluate the impact on optical performance from controlled/articulated optics, structural dynamics, anti thermal response, which arc important considerations for future large optics missions. To investigate these critical relationships, a new optical system analysis tool has been developed called the Controlled Optics Modelling Package (COMP).[22,23] It is a computer program especially designed for modelling the optical line-of-sight, surface-to-surfarc diffraction, and full wave front performance of optical systems that are subjected to thermal and dynamic disturbances. COMP can accommodate the most common optical elements: flat and conic mirrors and lenses, reference surfaces and focal planes, as well as some uncommon optics, such as segmented and deformable mirrors. It can be used for stand alone analysis of optical tolerances and optical performance, or to provide the optics part of an integrated system model for error analysis and budgeting, or for system calibration and end-to-end simulation performance analysis. integration of COMP with emerging CSI analysis tools will make it possible to optimize the design of a combined control/structure/optics system for maximum optical performance. All of these capabilities make COMP an important new analysis tool which enables comprehensive investigations of complex optical system architectures such as those to be used for space and Lunar based telescopes and interferometers. COMP has already seen application to the FMI as well as to on-going NASA flight projects including Hubble Space Telescope and SIRTF. JPL is currently in the process of embedding COMP in a more comprehensive integrated analysis package called IMOS (Integrated Modeling of Advanced Optical Systems).[24] IMOS will enable end-to-end modeling of complex optomechanical systems (including optics, controls, structural dynamics, and thermal analysis) in a single seat work station computing environment. Version 1.0 of COMP as well as an initial version of IMOS have been completed and released, along with comprehensive User Guides. They are available through COSMIC.

The process of system design is one of synthesis. Analysis tools such as COMP and IMOS have value in this process in that they are able to quickly evaluate competing point designs. However, analysis tools in their own right do not enable direct design synthesis. The key challenge in design synthesis is performing trade off studies pitting competing objectives from differing subsystems against one another. Too often such studies are based solely on "engineering judgement" and arc wholly non-quantitative in their approach. The more complex the system, the more likely this is to be the case. JPL has recently completed work on an initial set of software algorithms (the Integrated Design Tool) that enables quantitative trade offs across the structural, optical, and control subsystems.[25] This design tool has been used to conduct a case study on the JPL Phase B Testbed that explores the trade-off between mass and performance in precision optical systems.[26] The result is a family of testbed designs that would simultaneously provide improved optical per-formance and decreased mass. The current software is also capable of optimizations that include placement and tuning of damping elements, and the utilization of optical performance metrics such as Strehl ratio and wavefront error.[27,28] This design optimization methodology promises to enable the generation of highly efficient, light weight, control/structure designs required to support NASA's future optical systems.

End-to-End Technology Testing

To demonstrate the solution to the FMI-class control challenge, interferometer technology evolution requires ground-based validation at the component level followed by a successful demonstration of end-to-end instrument

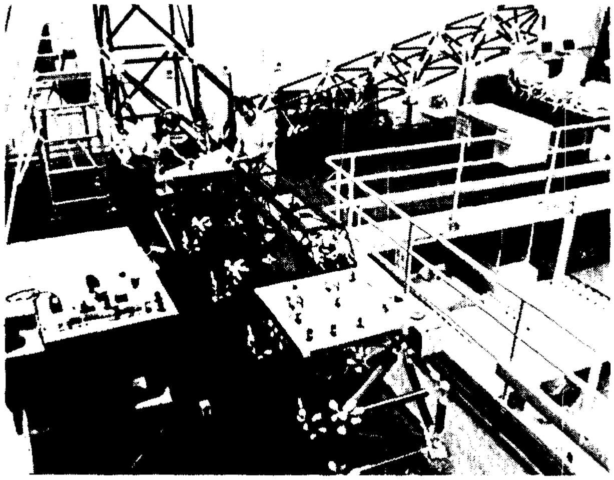

Fig. 19a. The Micro-1'recision Interferometer (MPI) Testbed.

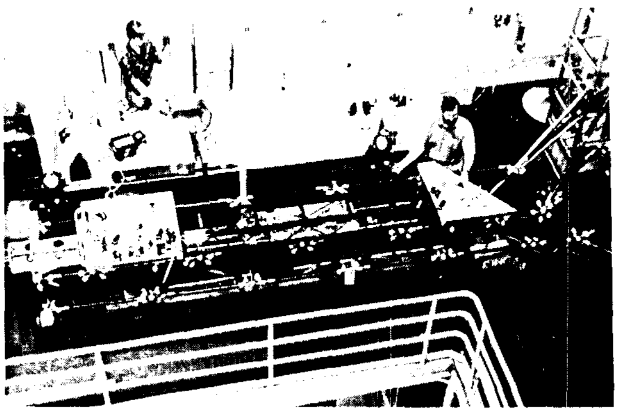

Fig. 19b. The MPI "optics Boom" Containing; the Interferometer Baseline (Lower Part **of Photo) and the** Star Simulator (on Opt ics 'J'able, Upper **Part** of Photo).

operation, first on the ground and then in space. Resulting technologies can then be applied 10 specific space-based interferometric missions or to other precision missions which exhibit similar challenging requirements.

'' ıe Micro-Precision Interferometer (MPI) Testbed

The Micro-Precision Interferometer (M Pl) Testbed[29-31] pictured in Figure 19 provides a crucial link between interferometric technologies developed for ground systems and those required for space. Its design draws upon extensive interferometer and CSI experience. The Mount Wilson Mark 11 I Interferometer is an operational ground-based instrument capable of performing astrometric measurements.[32] Although overall performance is limited by the atmosphere, this facility provides a demonstration that precision alignment and control of its optical elements can be achieved when the instrument is attached to a non-flexible body such as the earth. Results from the J}'), CSI Phase B Testbed, which includes a subset of the optical elements found on the Mount Wilson Mark I I I Interferometer, demonstı ate that the required nanometer level sensing and control requirements can be achieved on a flexible structure using the multi-layered architecture.

The Microl'recision Interferometer Testbed allows for system integration of CSI technologies with key interferometer subsystems on a flexible structure. The MI'] structure is a 7m x 6.8m x 5.5m truss weighing 200 kg (with optics and control systems attached the weight is about 600 kg). Built primarily from aluminum components, considerable effort was taken in the assembly process to minimize alignment errors and produce a linear structure. Three lit ıear extension springs attached to three different points on the structure make up the structure's suspension system. This system provides about a factor of ten separation between the structure's "rigid body" and flexible body modes (the lowest of which is at about 6 Hz).

The testbed was completed to the so-called Phase 1 Stage in June, 1994. Phase 1 connotes a full single interferometer baseline is in place on the truss structure (ultimately the Phase 2 testbed will contain two baselines). The equipment complement includes a three tier optical delay line with associated laser metrology, a pointing system complete with two gimballed siderostats, two fast steering mirrors, and coarse and fine angle tracking detectors, the six-axis isolation system pictured in Figure 12,anrtaliassociatcd electronics and real time computer control hardware necessaı y for closed loop system control and data acquisition. Initial closed loop operation was achieved in August, 1994 with "stellar" fringe stability of about 50 nanometers RMS recorded in the presence of lab ambient disturbances. Considerable work is yet to be done to attain the goal of 1 0 nanometers stability in response to a simulated on-orbit disturbance environment. Nevertheless, the community now has an "existence proof' of end-to-end interferometer operation on a free-free flexible structure representative of a first generation space optical interferometer.

Using a "stars simulator" laser metrology system located on a floated optical bench alongside the testbed, the sensitivity of "stellar" optical pathlength (from the "star," down each arm of the interferometer, and through the delay line) to mechanical excitation originating at the isolation fixture can be investigated. Figure 20 shows the transfer function from a shaker mounted on the isolat ion fixture to the stellar optical pathlength with the delay line control loops off. Note the testbed's lightly damped resonances (measured in previous modal surveys to have damping on the order of 0.1 %), indicative of an extremely linear structure. Note also that,

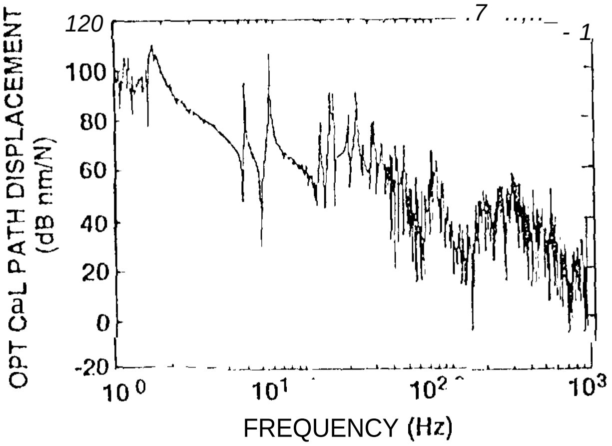

Fig. 20. MPI Test bed Open Loop Transfer Function from Shaker on isolation Fixture to Stellar Optical Pathlength (Nanometers per Newton vz. Hertz).

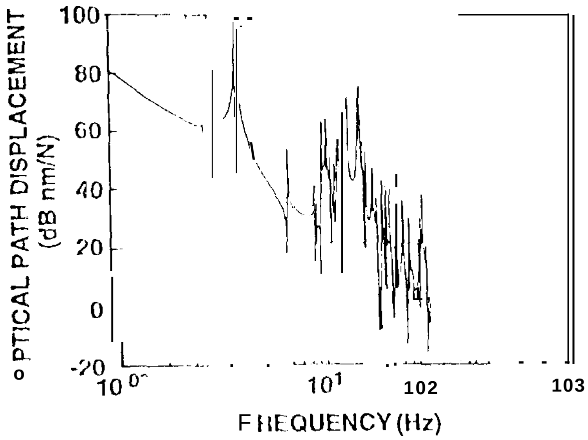

Fig. 21. FMI Open Loop Transfer Function from Reaction Wheel to Stellar Optical Pathlength (Nanometers per Newton vz. Hertz).

open loop, optical pathlength error exceeds 1 000 nanometers per newton across a broad frequency range. By way of comparison, refer to Figure 21 for the analogous (analytically derived) transfer function for the FMI. Notice the striking similarity between the FMI and the MPI transfer functions. This, of course, is no accident. The MP1 was designed to be a half scale reproduction of a "one-arm" FMI. If there is a surprise it is that the MPI, although a considerably smaller structure, appears to be somewhat more sensitive to mechanical excitation than the FMI, perhaps indicating that analytical models of such systems err on the side of optimism in predicting system performance. This, along with a host of other issues involving hardware and software validation, will be investigated in great detail as MPI testing proceeds through 1995 and into 1996.

Interferometer Flight Experiments

The MPI Testbed will go a long way toward establishing end-to-end interferometer technology readiness. However, for a handful of key components, there. is no substitute for the space environment to unambiguously provide performance verification. Two examples are vibration isolation and active delay lines. For the former, testing in 1-g invariably leads to the introduction of gravity off-load mechanisms which cast doubt upon the validity of the results. Similarly for the latter, gravity plays a poorly understood role in preloading critical mechanical elements, making extrapolation from ground based to space based performance extremely difficult. Prudent risk reduction in these areas indicates that testing in space is called for. Furthermore, from a psychological point of view, the excitement and impact of a space experiment should not be underestimated. "Flight proven" is a term that inspires confidence in the minds of program managers.

Two flight experiments aimed at interferometer systems technology are currently in Phase A under NASA's IN-STEP (In Space Technology Experiment) Program. The Six Axis Smart Strut Isolation Experiment (SASSIE) will explore on-orbit performance of a strut-based six-axis vibration isolation system. A more ambitious experiment, the Stellar Interferometer Tracking Experiment (SITE) will demonstrate end-to-end optical interferometer performance in the space shuttle's cargo bay (Figure 22). SITE will contain an optical delay line and will establish the performance credentials of this component in zero gravity.

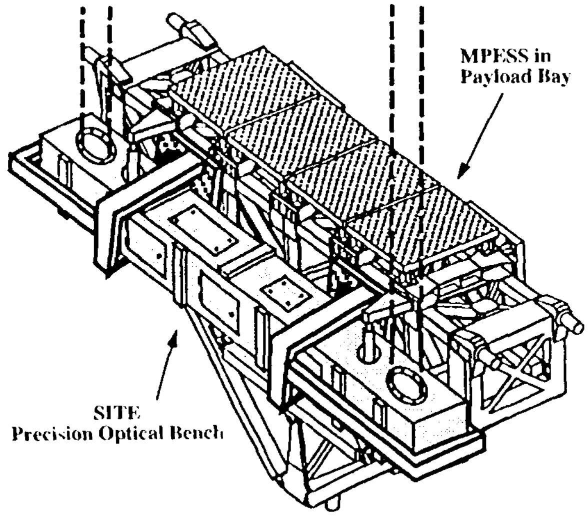

Fig. 22. SITE on the MPESS in the Shuttle Bay.

Summary

This paper has presented a broad brush overview of the JPL program in interferometer technology development and the NASA mission requirements to which it is responding. The program has been pursuing a plan that combines hardware development (components for picometer laser metrology and sub-micron structural control, vibration isolation, and optical element articulation), software development (integrated analysis tools such as COMP and IMOS as well as the Integrated Design TooJ), and the development of an overall system philosophy (viz., the multi-layer architecture). To date, analytical results on the Focus Mission Interferometer and experimental results on the Phase B Multi-Layer Testbed demonstrate the promise of the technology. What remains is the demonstration of technology flight readiness via end-to-end testing on the Micro-Precision Interferometer Testbed and on-orbit demonstrations on SITE and SASSIE. This should lead to wholesale insertion of interferometer technology into NASA flight missions by early in the next decade.

Acknowledgment

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